α PARTICLE MOMENTUM DISTRIBUTIONS FROM ^{12}C DECAYING RESONANCES

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The computed α particle momentum distributions from the decay of low-lying ^{12}C resonances are shown. The wave function of the decaying fragments is computed by means of the complex scaled hyperspherical adiabatic expansion method. The large-distance part of the wave functions is crucial and has to be accurately calculated. We discuss energy distributions, angular distributions and Dalitz plots for the 4^+, 1^+ and 4^- states of ^{12}C.

1. Introduction

The ^{12}C resonances below the proton separation threshold have been intensively studied over many years, motivated partly by its astrophysical importance. There are still many unanswered questions, e.g., what are the energies, angular momenta, structure, and decay properties of the resonances. Open questions still remain on the 0^+ and 2^+ resonances. The existence of the latter was conjectured by Morinaga in the fifties as a member of the rotational band with the 0^+ resonance at 7.65 MeV as band-head[1]. Several experiments recently provided new results but unfortunately yet for the position and width of the first 2^+ resonance, no agreement has been reached.

Three-body decay is important for studying different decay mechanisms, i.e. direct versus sequential. Direct decay takes place when all three particles leave simultaneously their interaction regions, while sequential decay proceeds via an intermediate 2-body state. The intermediate path of the decay process is not an observable, therefore the information has to be extracted from the distribution of the fragments after the decay.

We investigate in this contribution the decay of low-lying continuum states into three particle final states for the case of ^{12}C, assuming that the decay mechanism is

independent of how the initial state was formed. We describe the decay in analogy with α-decay, assuming that the three fragments are formed before entering the barrier at sufficiently small distances to allow the three-body treatment. Outside the range of the strong interaction, only the Coulomb and centrifugal barriers remain, since we have assumed that the small distance many-body dynamics is unimportant for the process. We show the momentum distributions of the fragments after the decay of the resonances by means of energy distributions, Dalitz plots and angular distributions. A comparison with oncoming experimental data is straightforward.

2. Faddeev equations and complex scaling

The decay of a ^{12}C resonance into three α particles is a pure three-body problem of nuclear physics. Therefore we describe ^{12}C as a 3α-cluster system. We use Faddeev equations and solve them in coordinate space using the adiabatic hyperspherical expansion method[2,3,4]. The hyperspherical coordinates consist in the so-called hyperradius ρ, defined as

$$\rho^2 = 4\sum_{i=1}^{3}(\vec{r}_i - \vec{R})^2 \;, \tag{1}$$

where $\vec{r}_i$ is the coordinate of the i-th α particle and $\vec{R}$ is the coordinate of the centre of mass, and five generalised angles. The angular functions are chosen for each ρ as the eigenfunctions of the angular part of the Faddeev equations. We must first determine the interaction V_i reproducing the low-energy two-body scattering properties. In this case, we have chosen an Ali-Bodmer potential[5] slightly modified in order to reproduce the s-wave resonance of ^{8}Be. The energy of the resonance is corrected by including a diagonal three-body interaction $V_{3b} = S\exp(-\rho^2/b^2)$. This three-body potential should effectively mock up the transition between the N- and three-body degrees of freedom, while the structure of the resonance is maintained.

The momentum distribution of the decay fragments is determined by the Fourier transform of the coordinate-space wave function. The hyperspherical harmonics transform into themselves after Fourier transformation. It has been shown[6] that the angular amplitude of the momentum-space wave function of the resonance is directly proportional to the coordinate-space one for a large value of ρ. Numerically converged results in the appropriate region of ρ-values are then needed in order to have a reliable computation. The probability distribution is obtained after integration over the four hyperangles describing the directions of the momenta,

$$P(k_y^2) \propto P(\cos^2\alpha) \propto (\sin 2\alpha)\int d\Omega_x\, d\Omega_y\, |\Psi(\rho,\alpha,\Omega_x,\Omega_y)|^2 \;. \tag{2}$$

The asymptotic behaviour is reached for hyperradii larger than about 60 fm. There is a small variation of the distribution from 70 to 100 fm, that shows the stability and convergence of the computation. We have chosen 80 fm as the value of ρ where the energy distributions should be computed. We have performed a Monte Carlo integration over the phase space to get the probability distributions.

3. Energy distributions and Dalitz plots

We find fourteen ^{12}C resonances below the proton separation threshold for most angular momenta and both parities. Small and intermediate distances are important for energies, widths and partial wave decomposition. Their structures have been previously described in detail[7]. Fig. 1 shows the adiabatic effective potentials for the resonances we are considering here, i.e. 4^+, 1^+ and 4^-. At relatively small distances the potentials have minima allocating the resonances. The barrier at intermediate distances determines the width of the resonance.
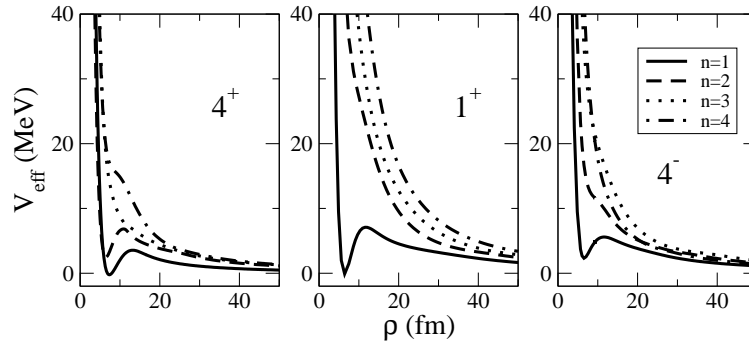

Fig. 1. The real parts of the four lowest adiabatic effective potentials (labeled by n), including the three-body potentials, for the 4^+ (left), 1^+ (centre) and 4^- (right) resonances of ^{12}C.

The energy distribution of the fragments after the decay is the only experimental information one can get, that allows us to study the decay path. Dalitz plots contain more information than single α energy distributions and constitute an easy way to see how the three particles share the energy after the decay of the resonance. The angular distribution reflects the preferred direction followed by one of the α particles with respect to the direction between the other two. It must also reflect the behaviour of the angular momentum and can be used to assign spin and parity of a measured state[8].

The *natural-parity states* of ^{12}C, i.e. 0^+, 1^-, 2^+, 3^- and 4^+, can breakup in a sequential decay via ^{8}Be(0^+). By exploiting the fact that precisely one of the adiabatic potentials asymptotically must describe the two-body resonance and the third particle far away, we are able to estimate the amount of sequential decay by looking at the complex scaled radial wave functions.

For the 4^+ state at an excitation energy of 14.1 MeV (or 6.83 MeV above the 3α threshold) we estimate that 20% decays via the ^{8}Be ground state. In fig. 2 we show the energy distribution for an α particle, the Dalitz plot and the angular distribution after removal of the sequential decay though the ^{8}Be ground state. The distribution of the kinetic energy of the particles is rather diffuse, and the Dalitz plot is smeared out. This is in contrast with the sequential decay distribution,

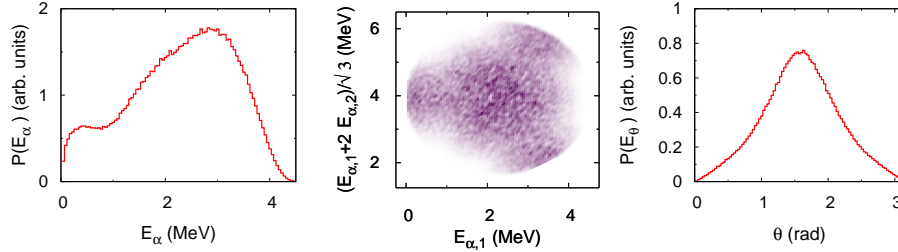4   R. Álvarez-Rodríguez, A.S. Jensen, D.V. Fedorov. H.O.U. Fynbo and E. Garrido

Fig. 2. α particle energy distribution (left), Dalitz plot (centre) and angular distribution of the directions between two particles and their centre of mass and the third particle (right) for the 4^+-resonance of ^{12}C at 6.83 MeV above the 3α threshold at 7.275 MeV. The contribution from the decay through ^{8}Be(0^+) has been removed.

where one of the particles stays at high energy and the other two at low energy. The angular distribution exhibits one smooth peak around $\pi/2$.

For the *unnatural-parity states* of ^{12}C, i.e. 1^+, 2^-, and 4^-, angular momentum and parity conservation forbid the decay via ^{8}Be(0^+).
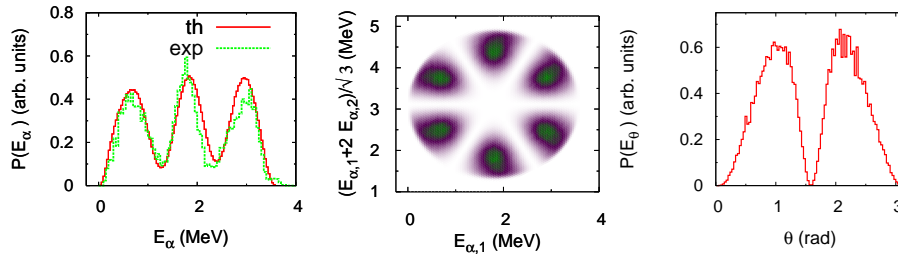

Fig. 3. α particle energy distribution (left), Dalitz plot (centre) and angular distribution of the directions between two particles and their centre of mass and the third particle (right) for the 1^+-resonance of ^{12}C at 4.52 MeV above the 3α threshold at 7.275 MeV.

Fig. 3 shows the individual α particle energy distribution, the Dalitz plot and the angular distribution for the 1^+ resonance of ^{12}C. The 1^+ state at an excitation energy of 12.7 MeV (or 5.42 MeV above the 3α threshold) is referred to as a shell-model state, which means that it has no cluster structure. But at large distances, after the decay takes place, we are dealing with a three-body problem. A 3α cluster description seems then to be the most natural treatment for this system. For the single α energy distribution the agreement with the experiment[9] is almost perfect[10]. The theoretical Dalitz plot can also be compared with the experimental one[11]. It is clear that our computation reproduces the pattern obtained from the

experimental data. In the angular distribution we obtain a minimum at $\pi/2$, which reflects the intrinsic angular momenta used to construct the wave function.
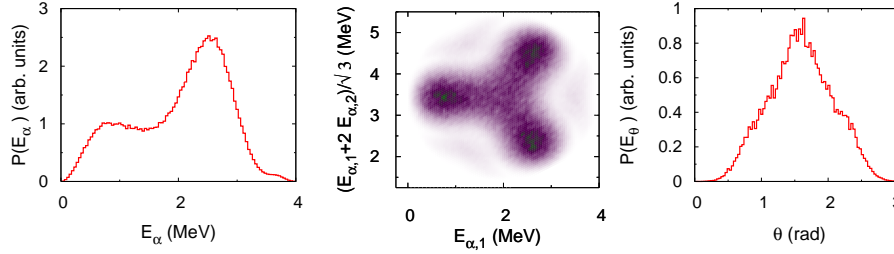

Fig. 4. α particle energy distribution (left), Dalitz plot (centre) and angular distribution of the directions between two particles and their centre of mass and the third particle (right) for the 4^--resonance of ^{12}C at 5.98 MeV above the 3α threshold at 7.275 MeV.

In our computation we obtain one 2^- and one 4^- state. We suggest the latter should correspond to the state at 13.35 MeV of excitation energy (or 6.08 MeV above the 3α threshold)[12] for which a preliminary spin-parity of 2^- is assigned by Azjenberg-Selove[13]. A new spin-parity assignment regarding the 2^- and 4^- states has been also recently suggested by Freer et al.[14].

Fig. 4 shows the α energy distribution after the decay of the 4^- resonance of ^{12}C. It consists of a low peak at small energies and a higher peak at larger energies. Oddly we get a very similar energy distribution for the 2^- resonance at 11.8 MeV. However, both the Dalitz plots and the angular distributions differ more from each other[8].

We have compared our results with some preliminary data from the reaction ^{11}B(^{3}He,d$\alpha\alpha$) studied at CMAM (Madrid) by M. Alcorta and collaborators in 2008[15]. Even though the analysis of the data is not yet finished, we find a very good agreement between the measured and the theoretical energy distributions, angular distributions and Dalitz plots.

4. Summary and conclusions

We predict the α-particle momentum distributions of the decaying low-lying ^{12}C many-body resonances. We use a pure three-α cluster model to describe all states at all distances. We mock up the small-distance many-body properties by a structureless three-body interaction adjusted to reproduce the resonance energy.

The natural-parity state 4^+ and the unnatural-parity states 1^+ and 4^- are used as examples. We show α particle energy distributions, Dalitz plots and angular distributions. Preliminary experimental data seem to agree very nicely with the theoretical predictions.

Acknowledgements

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